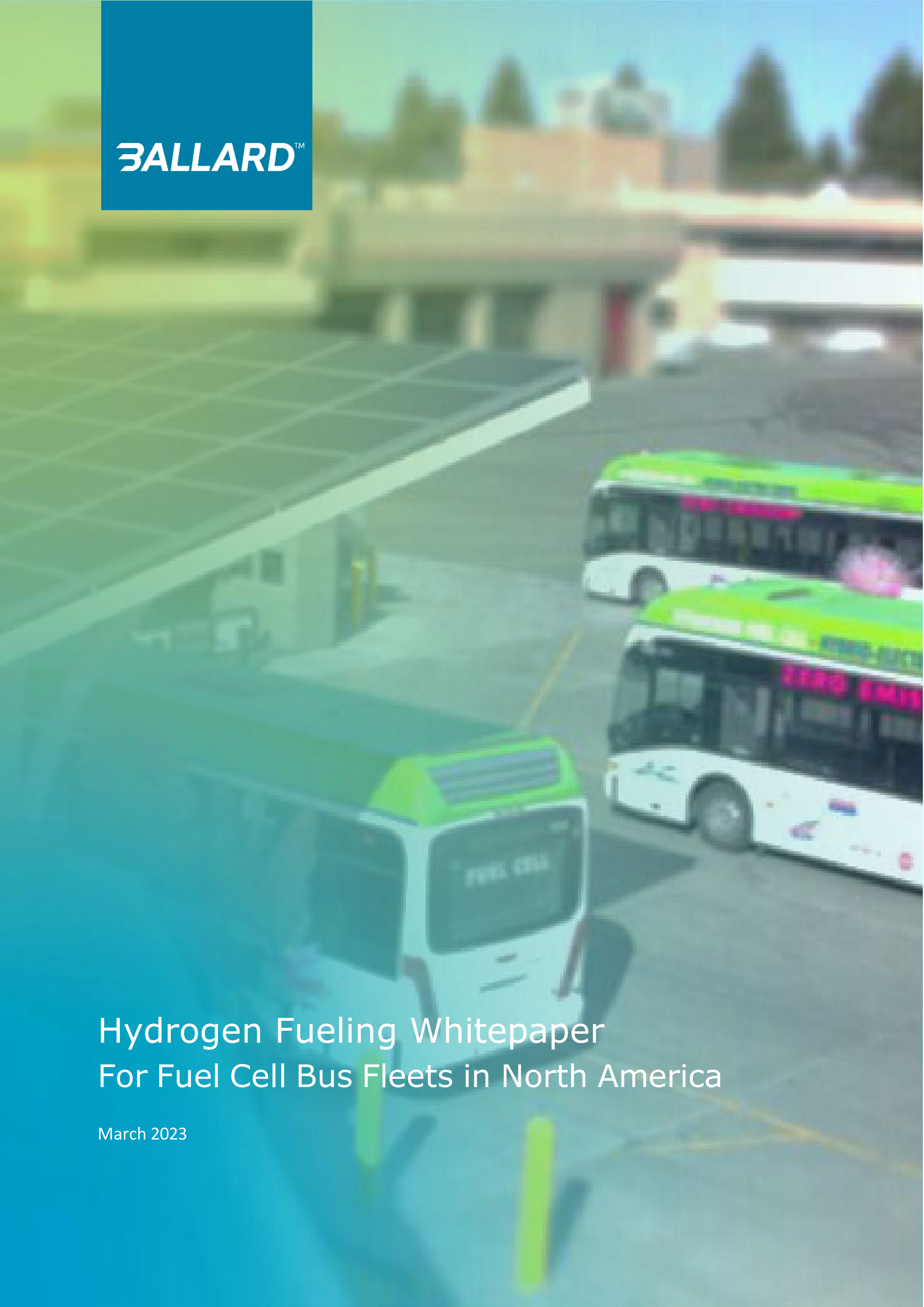

BALLARD™

Hydrogen Fueling Whitepaper
For Fuel Cell Bus Fleets in North America

March 2023

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Introduction

Hydrogen fuel cell powered vehicles have the potential to significantly reduce the environmental impact of transportation in comparison to vehicles powered by internal combustion engines. Major automakers have intentions for the majority of cars sold by 2030 to be electrified in some way - including hydrogen fuel cell vehicles. To date, a roadblock in major deployments has been the lack of widespread hydrogen fueling infrastructure to serve passenger vehicle customers. This is changing rapidly as federal and regional governments globally are working collaboratively with industry to develop the required regulations, infrastructure and training required to produce and supply hydrogen for commercial and private fleets.

Mass transit applications have the potential to break down these deployment barriers, and fuel cell buses deployments are expanding rapidly at transit agencies around the world.

Figure 1: Fuel Cell Bus Being Refueled with Hydrogen

With centralized filling and increasing fleet sizes, the deployment of fuel cell buses is providing an ideal opportunity to reduce the cost of hydrogen infrastructure and fuel. However, the success of these deployments will depend on a safe, convenient, and clean hydrogen generation and delivery infrastructure.

This paper will provide an overview of the hydrogen supply options available to transit agencies and guide readers in sourcing the appropriate fueling infrastructure and hydrogen supply for their fuel cell bus fleet.

Hydrogen Infrastructure at the Bus Depot

Transit agency deployments around the world have proven fuel cell buses can be fueled safely and efficiently, allowing normal refueling of buses at the end of each day, within the time window required, to be ready for service the next morning. Transit operators can rely on local industrial gas suppliers to be at the forefront of the development of hydrogen stations for bus fueling.

Options include permanent stations to fuel a fleet of transit buses or temporary installations for technology demonstration programs. Fleets operators can have hydrogen delivered in liquid or gaseous form or can also install their own hydrogen production facilities.

When considering the implementation of a hydrogen station, every transit property will be unique with regards to their specific requirements. It is not a one-size-fits-all situation related to budget and schedule for each specific property.

The following sections describe three phases that a typical transit agency will work through as the fuel cell electric bus fleet grows from a demonstration to a full-scale deployment.
These stages are designed to flexibly expand the hydrogen infrastructure to match the growing fuel cell bus fleet in a measured and economical way.

The Fundamentals of Fueling

Regardless of scale, a fully integrated fueling solution installed at a bus depot will include a **compression, storage and dispensing (CSD)** module to deliver fuel to the vehicle, including the hydrogen compression, high-pressure storage, and dispensing systems (Figure 2).

Hydrogen is dispensed to the vehicles at a pressure of 350-bar for most transit buses, or 700-bar for passenger cars and some truck applications.
Typically, the dispenser is located on a fueling island in line with normal bus fueling operations of wash, fuel, put away but may sometimes be packaged with the compression and storage systems in a "containerized" CSD module. Hydrogen fueling can be adjacent to CNG and diesel fueling.

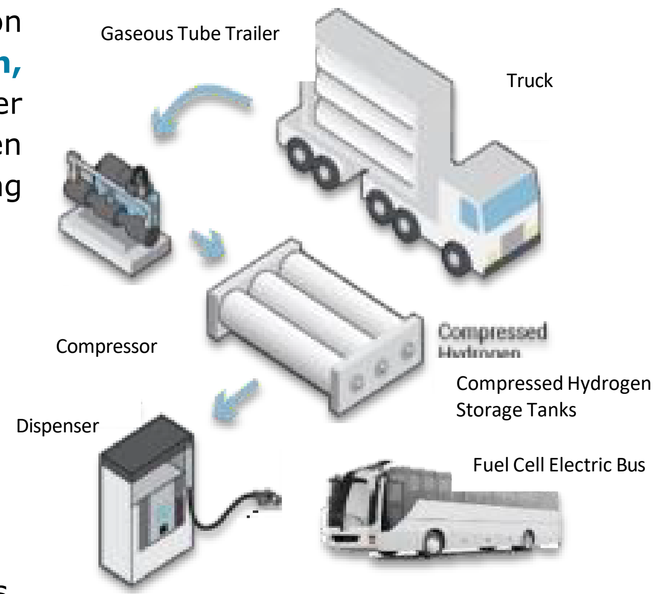


Figure 2: Compression, storage and dispensing (CSD) - (image courtesy of CAFCP)

Phase 1 - Demonstration Fleet (1 to 10 Buses)

Transit agencies will often demonstrate one to ten fuel cell electric buses before making the strategic decision to expand the fleet. Transit agencies at this stage in deployment are conducting an initial evaluation of the technology to gain a better understanding of the specific benefits to the operator and the riders.

The fueling infrastructure for this type of demonstration must be temporary or scalable, and not entail substantial changes to the operating environment at bus fueling facility.

Fuel cell electric buses will typically carry 35 to 60 kilograms of hydrogen and consume approximately 20 to 25 kilograms of hydrogen per day. A station for a demonstration fleet of five buses, for example, should be designed with a capacity of at least 125 kilograms per day.

This can be achieved with deliveries of gaseous hydrogen, for the lowest capital cost, or with liquid hydrogen for a solution that is more cost effective when scaled.

Availability of low-cost electricity or renewable natural gas can also enable on-site production of hydrogen, particularly when financial assistance is available for the capital equipment costs.

Phase 1: Fueling Solution

Supply and Infrastructure

The block diagram below illustrates a compressed gas delivery fueling pathway, with a trailer of pressurized storage tubes left at the fueling site and swapped with new deliveries as gas is consumed.

Recently manufacturers have begun offering mobile fueling trailers with liquid hydrogen. This can provide an excellent solution when liquid hydrogen supplies are the most abundant and lowest cost. This hardware is similar to the gaseous truck delivery shown above, with the addition of a liquid hydrogen storage tank, pump and vaporizer.

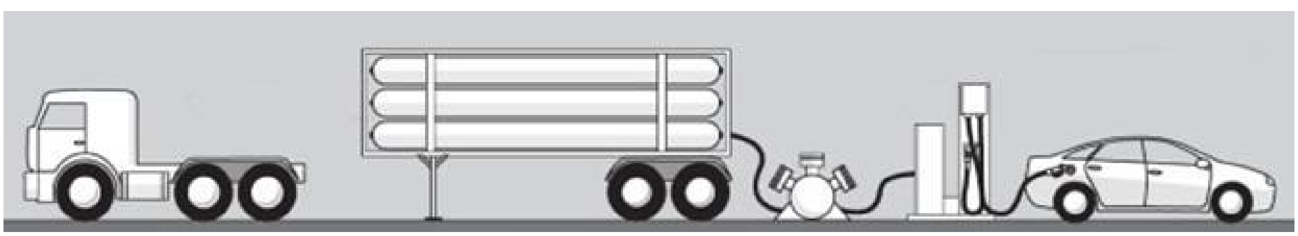
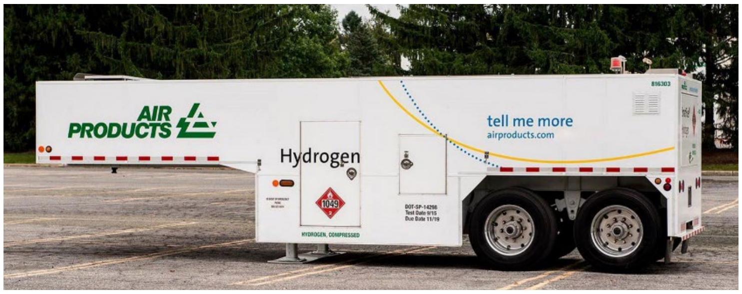


Figure 3: Demonstration Fleet Fueling Pathway with Delivered Gaseous Hydrogen

Cost

Rental of the tube trailer for delivery and storage of gas is estimated at approximately $12,000 USD per month plus service. The CSD system capable of delivering 125 kg per day is approximately $1.0 million USD. The fuel cost for delivered compressed gas is strongly influenced by the distance between the hydrogen production facility and the bus depot, ideally this is 100 miles or less for gaseous hydrogen delivery and 1,000 miles or less for delivery of liquid hydrogen.



In California, typical fuel costs for transit agencies ranges between $7.80 -$9.16 USD per kilogram, while costs in more remote regions may be higher. Gaseous hydrogen delivery can cost 4x that, which is one reason why liquid is always recommended.

Figure 4: Air products fueling trailer.

With a fuel cell electric bus fuel economy of 8 miles per kilogram, this translates into a fuel cost of $.97-$1.10 USD per mile.

Phase 1: Case Studies

SunLine Transit Agency,City of Indio.

Through a partnership between SunLine Transit and NICE America Research, liquid hydrogen pump technology and a mobile refueling system (Figure 5) is being piloted to offer hydrogen stations in the form of a mobile trailer.

Figure 5: NICE America Research Liquid hydrogen fueling trailer.

Golden Empire Transit, Bakersfield

Golden Empire Transit (GET) is the mass transportation provider in Bakersfield, California, transporting more than six million passengers per year. GET has committed to transition its fleets to 100% zero-emissions by 2040 in accordance with the Innovative Clean Transit (ICT) regulation.

In 2020, GET acquired its first 5 fuel cell electric buses from New Flyer. Since the lead times for the purchasing, construction, and commissioning of a permanent hydrogen fueling station was greater than one year, GET initially deployed a temporary hydrogen fueling solution with a capacity of 150kg/day to serve these buses until permanent fueling infrastructure was constructed.

After this first deployment, the mobile gaseous hydrogen storage and fueling infrastructure was replaced in 2021 by a more permanent liquid hydrogen infrastructure (capacity of 300kg/day) as another 5 FCEB were deployed.

GET also modified the existing maintenance facility to be compliant with FCEB repair garage safety codes and standards. This upgrade of the entire facility was estimated at $1.1 million.

The Champaign-Urbana Mass Transit District, Champaign, Urbana

The Champaign-Urbana Mass Transit District (MTD) is a transit agency servicing Champaign, Urbana, and Savoy residents as well as the University of Illinois. With a current fleet of 114 coaches in operation, most of which are hybrid, MTD seeks to help their community thrive with reliable, efficient transportation. As part of its sustainability initiatives MTD deployed the operation's first two 60-foot hydrogen fuel cell electric buses in 2021.

Figure 6: Hydrogen Refueling Station by BayoTech

These buses were part of a larger project which also included modifications to MTD's maintenance and storage facility, design and construction of an onsite hydrogen production station, and a solar array.

It was a challenge to align the timing of all four aspects of this complex project, especially with a global pandemic impacting availability of resources. As the delivery of the buses was expected before the completion of hydrogen station, MTD needed a temporary solution to fuel the buses with hydrogen.
BayoTech was selected to provide hydrogen fuel and fueling infrastructure to bridge the gap with its gaseous mobile trailer solution. (Figure 6)

Anteater Express, University of California

The National Fuel Cell Research Center was awarded a contract by the California Energy Commission to build and demonstrate a fuel cell bus for operation at the University of California's Irvine (UCI) campus.

Figure 7: Hydrogen Refueling Station by Air Products

The addition of the hydrogen fuel cell bus to the UC Irvine Anteater Express fleet is the first of its kind to operate on a University of California campus. UCI's hydrogen fueling station was constructed in 2015 and is designed to fuel both the bus and fuel cell passenger vehicles operating in the region.

The station features the Air Products "S700" compressor, with fuel supplied via a 250 kg gaseous hydrogen tube trailer delivered to the site, then swapped out once depleted.[1]

Designed to dispense 100 kg/day (equivalent to 100 gallons per day of gasoline), up to fifteen fuel cell vehicles and two fuel cell buses can be refueled per day. The station has been designed with the capability of accepting 500 kg tube trailers to easily double the capacity as demand grows.

[1] National Fuel Cell Research Center. "UC Irvine Hydrogen Station." University of California, Irvine. http://www.nfcrc.uci.edu/3/research/keyInitiatives/hydrogen/IrvineHydrogenFuelingStation.aspx (accessed June 20, 2016).

Phase 2 - Pilot Deployment (10 to 50 buses)

At the next stage, a pilot deployment of fuel cell buses is typically in the range of ten to fifty buses. Transit agencies at this stage of deployment have conducted an initial evaluation of fuel cell technology. Operators recognize the business and performance benefits of fuel cell buses and are integrating the zero-emission buses into their normal operations.

At this level of consumption (200 -1000 kilograms per day), the installation is not temporary, and the dispenser will usually be set up in line with the compressed natural gas (CNG) or diesel buses in order to maintain fueling operations continuity.

Phase 2: Fueling Solution

Supply and Infrastructure

Delivered liquid hydrogen storage often provides the most economical infrastructure option for this size of fleet. This hydrogen is produced at a large-scale industrial liquification facility, and delivered via cryogenic transport trailer for storage on-site.

This attractive solution is scalable overtime and allows the addition of on-site hydrogen production by electrolyzer or SMR to further diversify sources for resiliency and cost optimization.

The block diagram below illustrates the delivered liquid hydrogen fueling pathway.

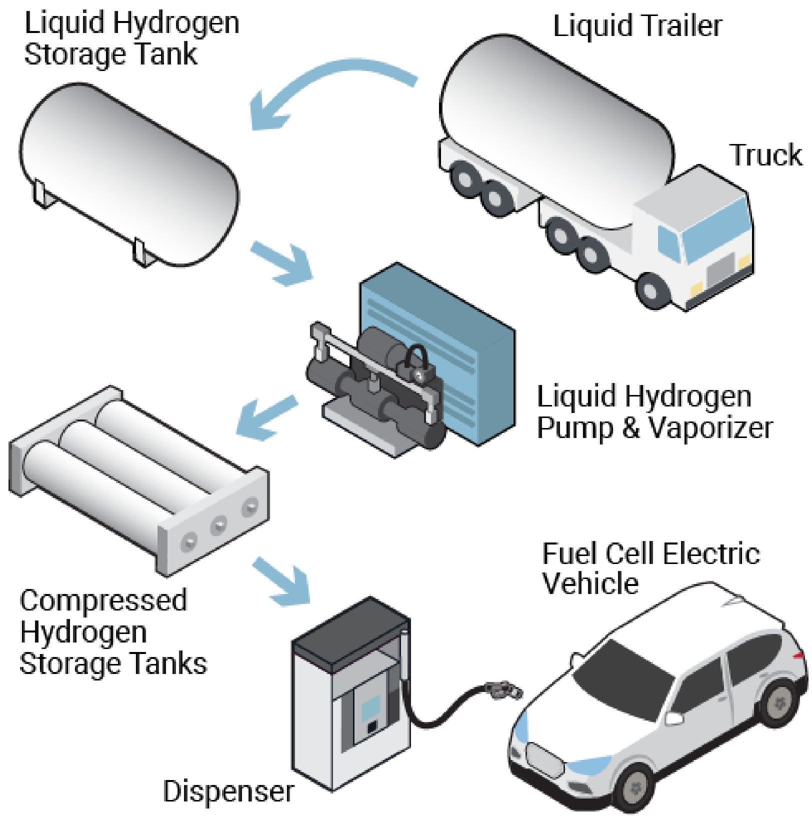


Figure 8: Pilot Deployment Fleet Fueling Pathway with Delivered Liquid Hydrogen (image courtesy of CAFCP)

Cost

Transit agencies may purchase liquid hydrogen fueling equipment outright, which may be appealing when capital funding sources are available.

Alternatively, the industrial gas provider can often provide full turn-key solutions to install, maintain, and operate and retain ownership of the fuel storage tank and CSD, for a defined monthly fee or a single "all-in" price for each kilogram of fuel.

As compared with delivered gaseous hydrogen, fuel costs are much less dependent on proximity to hydrogen production sources, however it is necessary to carefully align the supply and demand for hydrogen to minimize routine nominal "boil-off". This boil-off of fuel is only 1% of tank volume per day and can sometimes be further reduced to 0.1% - 0.5% with new tank technologies or economizer capture solutions.

Infrastructure equipment costs are approximately $3-7 million USD, including the vaporizer, cryo pump, high-pressure storage systems and a dispenser, for a fueling capacity of up to 50 buses per day.

Phase 2: Case Studies

AC Transit, California

AC Transit is one of the largest transit agencies in California, serving over 60 million passengers a year throughout a 364-square mile region. AC Transit currently operates a fleet of thirteen fuel cell buses, with an additional ten buses planned for delivery in the coming years. AC Transit fuels the fleet with a combination of liquid hydrogen and on-site electrolysis.

Scheduling and service requirements make it necessary to fuel the buses between 11 p.m. and 5 a.m., and the fast fueling afforded by hydrogen CSDs enables the buses to stay in continuous service from 5 a.m. to 11 p.m.[2]

Excluding the implementation and capital costs for the hydrogen station equipment, the combined cost of operation, maintenance, and hydrogen to fuel buses at this station is approximately can be found in the AC Transit Report. "Zero Emission Transit Bus Technology Analysis Volume 4". AC Transit. https://hydrogen.stanford.edu/publications/ac-transits-zero-emission-transit-bus-technology-analysis-volume-4 (published June 2, 2022).

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[2] California Fuel Cell Partnership. "A Road Map for Fuel Cell Electric Buses in California." CAFCP.org http://cafcp.org/sites/default/files/A%20Roadmap%20for%20Fuel%20Cell%20Electric%20Buses%20in%20California.pdf (accessed June 20, 2016).

Oakland Hydrogen Station Overview

Year Built: 2014

Total Cost: $6.3 million

Fueling capacity: Thirteen buses per 12-hour fueling window.

Station Equipment: 9,000 gallon liquid hydrogen storage tank, ambient vaporizers, an IC-50 ionic compressor, and 360 kg of high-pressure gaseous storage

Hydrogen Production: Electrolyzer (65 kg of green hydrogen per day).

Maintenance: O&M agreement

Maintenance Monthly Cost: $14,833 (covering operations, preventative maintenance, and corrective maintenance)

Liquid hydrogen tank maintenance: $3,800

Operations: Operations includes maintaining a remote monitoring and alarm system to support 24/7 operations, including the immediate dispatch of a technician upon alarm. Preventative maintenance includes regular and planned activities to all equipment on a weekly, monthly, or annual basis. Monthly inspections and certifications of liquid storage (hydrogen or nitrogen) are also included.

Note: The District plans to upgrade the Oakland hydrogen station with liquid pumps once funding is secured. Two dispensers were installed in the fuel island that are aligned with the diesel dispensers making the bus servicing process seamless.

The Emeryville Hydrogen Station Overview

At AC Transit's hydrogen station in Emeryville, California, solar- powered electrolysis produces hydrogen from water. With no emissions generated during the production or consumption of the hydrogen, this truly is a zero-emission solution on a well to wheels basis.

The first phase of the Emeryville Station has the capacity to rapidly fuel 12 buses consecutively with more than 30 kilograms of hydrogen each, a time comparable with refueling diesel buses.

Fueling capacity: 12 buses (30 kg of hydrogen each) **Hydrogen Production:** Solar-

powered electrolyzer **Maintenance:** O&M Agreement

Maintenance Monthly Cost: $11,851 (covering operations, preventative maintenance, and corrective maintenance)

Hydrogen tank maintenance: $5,950 for liquid hydrogen tank, and $600 nitrogen tank maintenance

Operations: Maintaining a remote monitoring and alarm system to support 24/7 operations, including the immediate dispatch of a technician upon alarm. Preventative maintenance includes regular and planned activities to all equipment on a weekly, monthly, or annual basis. Monthly inspections and certifications of liquid storage (hydrogen and nitrogen) is also included.

OCTA, California

In Southern California, Orange County Transportation Authority (OCTA) expanded from a single bus demonstration to a fleet of ten fuel cell electric buses.

They have transitioned from temporary fueling to a scalable liquid fueling station, to suit their plans to replace the remainder of their 40' low-floor fleet with over 300 fuel cell electric buses as part of the zero-emissions transition plan.

Figure 9 : Orange County Transportation Authority (OCTA) bus

The new fueling station, located at OCTA's bus depot, is equipped with Air Products'SmartFuel hydrogen fueling technology, design and equipment. OCTA's current hydrogen fuel cell electric bus fleet is comprised of 10 buses, but the station is built for future growth.

It has a bus fueling capacity for up to 50 buses, which corresponds to fueling up to 1,500kg of hydrogen in an eight-hour time period. The station can fuel transit buses with an average of 28 kg of H2 per bus in a time frame of 6 to 10 minutes per bus, while also providing back-to-back bus fueling for up to 30 buses and simultaneous fueling capability with multiple fueling lanes.

Metric	Value (Feb 2020-Feb 2021)
Number of fuel cell buses	10
Miles traveled	~300k
Average fuel economy	8.46mi/kg H2 / 9.56mi/DGE
Average fueling rate	3.0 kg/min
Time to fuel each bus	5-10 min

Figure 10: Fueling data over 1 year of operation (OCTA Operations)

Phase 3 – Commercial Deployment (50+ buses)

Commercial deployment is typically greater than fifty fuel cell buses. Transit agencies at this stage in deployment have fully embraced zero-emission fuel cell bus technology and are ready to invest in the fueling infrastructure to support a significant fleet of buses.

One of the advantages of fuel cell electric buses over other zero-emission technologies is the ability to scale up the fueling infrastructure without requiring substantial changes to vehicle operations or substantial modifications to the electrical grid.

Phase 3: Fueling Solution

Supply and Infrastructure

There are two fueling pathways suitable for this size of fuel cell electric bus fleet: 1) delivered liquid hydrogen, or 2) on-site hydrogen production through electrolysis or steam methane reforming (SMR); including various combinations of the two. The development of large hydrogen production plants and hydrogen hubs will allow transit agencies to consider hydrogen pipelines as another pathway to the molecule in specific areas.

Looking at off-site production solution, the equipment used for a commercial liquid hydrogen fueling station would be similar to that illustrated in Figure 8, with additional dispensers to allow streamlined fueling operations. Depending on the size of the storage tank, liquid hydrogen delivery would be 1 -2 times per week, during off-peak hours.

While considering a fueling model with delivered hydrogen, the cost of a kilogram of hydrogen will be most likely dictated by the distance to the hydrogen production facility and the production process. In specific use cases where the production is close enough to the refueling assets, hydrogen pipelines could be considered but would require a minimal daily consumption threshold to justify the investment.

On-site hydrogen production is another option to consider at this scale but this will obviously require a significant investment. However, this approach can provide security of supply, especially when it is backed up with the possibility of delivered hydrogen in the event of scheduled or unscheduled equipment shutdown.

Depending of the natural resources available and the carbon intensity of the grid, transit agencies could either consider an electrolyzer or a SMR (steam methane reforming) unit.

The SMR production process is based on the “cracking” of compressed natural gas (methane) to produce hydrogen fuel. For agencies with compressed natural gas bus fleets, this is often an attractive option as the fuel feedstock (methane) is common for both bus technologies.

Figure 11: BayoTech’s first market-ready on-site hydrogen production generator, shown here, fits into a 40-foot cargo container for shipping to any location. (Courtesy of BayoTech)

Electrolyzers are very promising, especially when coupled with a local green electricity production. Investments (CAPEX) are nevertheless quite significant and the cost of the hydrogen produced is very sensitive to the cost of electricity. A low electricity price is essential to produce competitive green hydrogen. The DOE is targeting a 1$/kg of green hydrogen in 2030.

Cost

For an on-site SMR solution capable of delivery up to 700 kilograms of hydrogen per day, the capital costs for infrastructure would include the reformer ($2.5 -$3.5 million USD), and other equipment costs of approximately $3.0 -5.0 million USD, including the compressor, high-pressure storage systems, and multiple dispensers to service a fleet this size. The fuel cost for hydrogen derived from SMR at this scale is typically $3 – 6 USD per kilogram.

With a fuel cell electric bus fuel economy of 8 miles per kilogram, this translates into a fuel cost of $0.38 -0.75 USD per mile.

For an on-site electrolyzer capable of producing about 880kg/day, a 2 MW electrolyzer will be required. The cost for such an electrolyzer will be around $2.5 to $4 million USD - installation included, plus about $2 million USD for compression systems. A storage system will be also installed ($ 50k -$ 100) and the dispenser unit (with an integrated chiller) should cost around 400 - 500k$.

Phase 3: Case Studies

SunLine Transit Agency, California

SunLine has been a pioneer in alternative fuels for the past three decades, with initial tests of hydrogen fuel cell buses in 2000. SunLine now operates 21 total hydrogen fuel-cell vehicles, and is on track to convert all vehicles to zero-emissions by 2035 – five years ahead of the deadline set by state mandates.

To support the growth of the hydrogen fuel cell fleet, Sunline has set up the largest hydrogen electrolyzer fueling station dedicated to transit in the U.S, complementing its stand-alone liquid hydrogen station.

SunLine worked with NEL on all aspects of the hydrogen station and electrolyzer construction which included siting, permitting, civil and electrical work, installation, and commissioning. NEL also provided technical expertise and training to SunLine including emergency first responders for the hydrogen station operation, servicing and maintenance, and safety and emergency protocols.

The NEL fueling equipment includes a PEM electrolyzer utilizing a minimum 33% renewable energy, and compression, storage, and dispensing equipment. This 350-bar station is capable of producing 900 kilograms of hydrogen per day, enough fuel for 30
-35 buses in normal revenue service. The total cost of this new installation was $ 8.3 million USD.

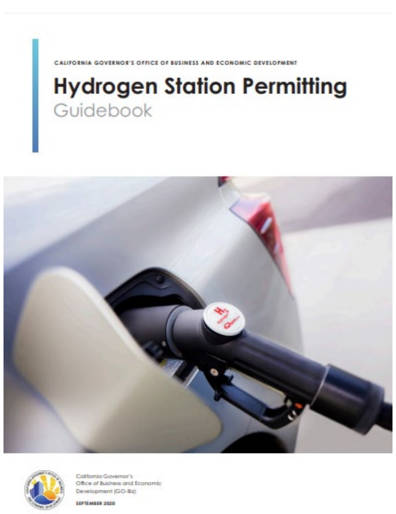
The liquid hydrogen station includes storage, a liquid hydrogen pump, and dispensing stations. The station was developed by NICE America Research to be scalable to bring flexibility to the fleet operator. Together, the hydrogen electrolyzer and liquid hydrogen station is capable of fueling 57 fixed route fuel cell electric buses and 39 paratransit fuel cell electric buses. The completed liquid hydrogen station is expected to be operational by the end of 2023.

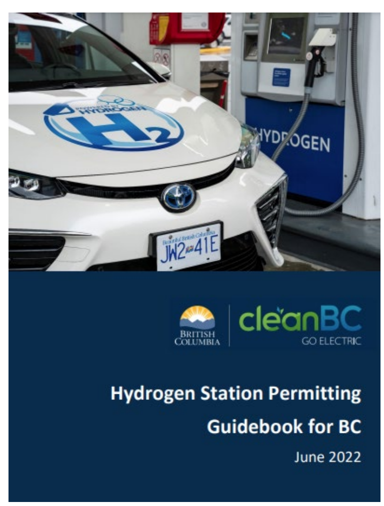
Figure 12: SunLine refueling station (Courtesy of Sunline)

Hydrogen Station Development

Think of the roadmap required to move forward with a hydrogen station for the transit fleet. The Framework to support a onsite hydrogen station development will require several reviews and departments who will be engaged during the development process.

These include local permitting offices who will review local setbacks, zoning, site plan reviews and municipal approvals. The Province of BC and the Go-Biz Station Permitting Guidebook - has been developed to assist in the process installing the hydrogen infrastructure to support a fleet deployment. The resource can be found here:





Paying for the Hydrogen Infrastructure in the United States

In the United States, the Federal Transit Administration (FTA) has developed the Low or No Emission Vehicle Deployment Program (Low-No Program) to provide funding for both zero and low emission transit buses and the cost of leasing or acquiring transit bus-related equipment and facilities.

Under the Low-No Program, up to 90 percent of the net project cost of the equipment or facilities attributable to compliance with the Clean Air Act is covered through the FTA.

There are also similar State programs, such as the California Air Resource Board's (CARB) Air Quality Improvement Program (AQIP) and HVIP zero emissions heavy duty vehicle purchase incentive program. Programs like the California Energy Commission's EnergIIZE program can be used singularly or in combination with FTA funding to pay for hydrogen infrastructure to support deployments.

Congestion Mitigation and Air Quality Improvement (CMAQ) Program

The Congestion Mitigation and Air Quality Improvement (CMAQ) program provides a funding source for State and local governments to fund transportation projects and programs to help meet the requirements of the Clean Air Act (CAA) and its amendments and is codified at 23 USC Sec 149. CMAQ funds support state- and locally selected transportation projects that reduce mobile source emissions in both current and former areas designated by the U.S. Environmental Protection Agency (EPA) to be in nonattainment or maintenance of the national ambient air quality standards for ozone, carbon monoxide, and/or particulate matter.

Many types of projects are eligible under the CMAQ program including electric vehicles and charging stations, diesel engine replacements and retrofits, transit improvements, bicycle and pedestrian facilities, shared micromobility projects including shared scooter systems, and more. In addition to improving air quality and reducing congestion, CMAQ projects can improve equitable access to transportation services, improve safety, and promote application of new and emerging technologies.

BALLARD™

Transitioning from CNG Buses to Hydrogen Fuel Cell Buses

Unlike battery electric buses that require a total replacement of the existing fueling infrastructure, fuel cell electric buses allow transit agencies that are currently operating CNG buses to transition to a low and zero- emission fleet mix using a common fuel feedstock (methane) and leveraging the existing infrastructure.

A combination of low-emission CNG buses with zero-emission fuel cell electric buses would demonstrate an "integrated" solution from a common fueling supply chain under a model that is both economical and scalable to hundreds of buses (perhaps the 'Achilles heel' for battery electric buses).

Hydrogen and compressed natural gas share many of the same characteristics, making implementation easier:

- Similar codes and standards for the safe handling of Class 2 flammable gases
- Common distribution equipment up to the steam methane reformer; similar piping, compression, gas storage and dispensing systems
- Similar refueling procedures
- Similar regulatory process with fire marshal and planning departments other authorities having jurisdiction (AHJ)
- Similar leak detection systems
- Similar training and qualifications for technicians

With the Advanced Clean Transit rule making currently under review in California, it is likely that large fleets will be required to purchase and operate some percentage of their fleet as zero-emission vehicles.

For state transit agencies with large CNG bus fleets, on-site hydrogen production presents the opportunity to leverage existing assets to create a complementary zero- emission infrastructure, rather than starting from scratch.

The estimated cost to convert CNG maintenance facilities to hydrogen will vary from $500,000 to $1M (including engineering and equipment).

Hydrogen Infrastructure Suppliers

Every transit agency will have unique requirements impacting the choice of fueling technology. Suppliers of hydrogen infrastructure with experience supporting deployments of fuel cell buses in the United States include the following companies.

Contact these companies to find the right solution for each specific property.

Supplier	Fueling Technology	Reference Transit Sites	Contact
AIR LIQUIDE www.airliquide.com	Gaseous hydrogen delivered in tube trailer Bulk delivery of liquid hydrogen On-site SMR & Electrolysis	BC Transit, British Columbia, Canada Birmingham Jefferson County Transit Authority University of Delaware	Glidas Bonnier 713-653-3529
AIR PRODUCTS www.airproducts.com	Gaseous hydrogen delivered in tube trailer Bulk delivery of liquid hydrogen On-site reforming of natural gas	University of California, Irvine campus Stark Area Regional Transit Authority, Ohio OCTA	John Chimenti 503-710-0514 chimenjp@air products.com
BayoTech https://bayotech.us/	Hydrogen fuel delivery Composite cylinder-based hydrogen transport trailers and storage modules Onsite hydrogen generation units	Champaign Urbana MTD Purchased IGX Group in 2021	Hernan Henriquez Vice-President of Sales 949.373.6012 Hernan.Henriquez@bayotech.us Gustavo Gonzalez 437 988 4577 gus.gonzalez@bayotech.us
Clean Energy www.cleanenergyfuels.com	Hydrogen fueling stations Liquid hydrogen delivery	Foothill Transit	Derek D. Turbide Vice President, Business Development office 949.437.1305 | mobile 619.818.7186 dturbide@cleanenergyfuels.com
GenH2 https://genh2hydrogen.com/	Hydrogen fueling stations Mobile refilling systems and storage solutions Hydrogen production (SMR process)		Chris Wallington 219-613-0435| Chris@GenH2.net
HTEC (Hydrogen Technology and Energy Corporation) www.htec.ca	Fuel supply Mobile station (350 bars and 450 bars) Refilling stations (compressed or liquid H2) On-site storage	Refilling stations in service in California and British Columbia (Canada)	Pierre Gauthier 1-514-378-5037 pgauthier@htec.ca Shannon Halliday 1-604-417-8336 shalliday@htec.ca

IVYS www.ivysinc.com/hydrogen-dispensing-solutions	Producing a gaseous mobile fueler, providing the CSD system at Champaign Urbana	Champaign Urbana	Wesley Hansen, Director of Business Development, E-Mobility 617.435.7937 wes.hansen@ivysinc.com
LINDE GROUP www.linde.com	Fuel supply (bulk delivery of compressed and liquid) and on-site storage Production solutions (On-site electrolysis, etc.) Refueling stations	Alameda-Contra Costa Transit District, California	Stacey Grauer +1 (330) 398-6452 stacey.grauer@linde.com
MESSER www.messer-us.com	Hydrogen fueling stations Liquid hydrogen delivery		Wally Dubno Business Development Manager – Hydrogen Mobility Messer North America, Inc Mobile: +1-714-642-9546 wally.dubno@messer-us.com
NEL https://nelhydrogen.com/	On-site electrolysis	Alameda-Contra Costa Transit District, California Sunline , Palm Springs, California Champaign Urbana	Stephen Szymanski Director of Business Development, Projects and Government Nel Hydrogen 10 Technology Drive, Wallingford, CT 06492 USA Office: D +1 203-678-2338 M +1 203-980-3182 Fax: +1 203-949-8016 sszymanski@nelhydrogen.com www.protononsite.com
OneH2 https://www.oneh2.com/	Hydrogen on-site production systems Hydrogen fueling stations Mobile refilling systems		Paul Dawson President & CEO 844 99-ONEH2 ext. 701 Oneh2.com
TC Energy TCEnergy.com	Suppliers of liquid or gaseous hydrogen		Phillip Franshaw Power & Energy Solutions phillip_franshaw@tcenergy.com Office: (832)320-6248 Mobile: (346)405-1221
TRILLIUM https://www.trilliumenergy.com/	Turnkey hydrogen station (equipment, gas supply, operation & maintenance)	OCTA, Orange County, California, Champaign Urbana MTD, and NCTD (to come later 2022)	Ashish Bhakta Zero Emission Business Development Manager at Trillium Energy, Ashish.Bhakta@TrilliumCNG.com 713-332-5711 346-298-3880

Typical Fuel Supply	Average Fleet Consumption	Capital Costs (USD)	Delivered Fuel Cost	Fuel Cost Per Mile (USD)	Installation Footprint
PHASE I – Demonstration Fleet (1-10 buses)					
Compressed gaseous hydrogen in tube trailers, delivered mobile liquid trailer	Up to 200 kg/day	Tube trailer rental: $12,000/month Compression, storage and dispenser: $1 million	$15 - $35/kg for gaseous and $5-$9/kg for liquid	$1.25-$3.00/mile	Temporary deployment of 40’ trailer (20’ x 50’)
PHASE II – Pilot Deployment (10 to 50 buses)					
Liquid hydrogen storage	200 to 1000 kg/day	Vaporizer, pump, storage & dispenser: $3-5 million	$6 - $9/kg	$0.75 - $1.13/mile	40’ x 60’
PHASE III – Commercial Deployment (50+ buses)					
Liquid hydrogen storage or on-site SMR or electrolysis	>1,000 kg/day	On-site SMR: $2.5 – 3.5 million On-site Electrolyzer: $2.5 – $4 million Vaporizer, cryo-pump, storage & dispensers: $3-5 million	$3 - $6/kg	$0.38 - $0.75/mile	77’ x 60’

In addition to the type of hydrogen fuel production (SMR, electrolysis), there are several variables such as on-site vs. centralized production, fuel distribution method, buffer storage, dispensing rate etc. that have a major impact on the fueling infrastructure costs. Industrial hydrogen gas suppliers indicate that these values are an estimate only and must be validated for each individual proposed site.

As hydrogen infrastructure technology continues to mature, improvements will be made in solutions available to transit agencies. Hydrogen produced from renewable sources, such as solar, wind or biomass will become more prevalent and economical.

While this study provides a guideline for transit agencies transitioning to hydrogen fuel, agencies are encouraged to contact a regional gas supplier (as outlined in Section 8) to determine the ideal solution for a particular scenario.

Appendix I – Recent Fuel Cell Bus Fleets at US and Canada Transit Agencies[5]

Transit Agency	Fuel Cell Bus Fleet	Fueling Locations	Station Type	Supplier
AC Transit	30	Oakland, CA Emerville, CA	Bulk delivery of liquid hydrogen On-site electrolysis	Linde, Proton OnSite
SunLine Transit Agency (current)	22	Thousand Palms, CA	On-site reforming of natural gas	Hyradix
SunLine Transit Agency (2019)	21	Thousand Palms, CA	On-site electrolysis	Proton OnSite
SARTA	12	Canton, OH	Bulk delivery of liquid hydrogen	Air Products
Flint Mass Transportation Authority	1	Flint, MI	On-site electrolysis	Air Products, Proton OnSite
UCI Transportation & Orange County Transportation Authority	1	Irvine, CA	Bulk delivery of liquid hydrogen	Air Products
Orange County Transportation Authority	10	Orange County	Bulk delivery of liquid hydrogen	Trillium CNG
Edmonton Transit and Strathcona County	2	Edmonton & Strathcona County, Alberta	Bulk delivery of liquid hydrogen/under development	Suncor/HTech
Foothill Transit	33	Pomona	On-site liquid hydrogen station under development	Clean Energy Fuels
Champaign Urbana	2	Illinois	Green hydrogen on-site via electrolysis	Trillium Hydrogen

Figure 13: GEN H2 Liquid Hydrogen System

[5] National Renewable Energy Laboratory. "U.S. Fuel Cell Bus Projects." NREL.gov http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html (accessed June 20, 2016).

Appendix II - Hydrogen Supply Alternatives

Hydrogen is one of the most abundant elements, but it is rarely found in its purest form. Hydrogen fuel can be obtained from many sources, including natural gas, biogas, or other hydrocarbon fuels, as a by-product of chlor-alkali production, or from water through electrolysis. The base substance dictates the production process chosen. Each of these production methods has a varying environmental impact.

Hydrogen can be produced in large “central production” plants and transported to the point of end-use. Liquid hydrogen is the most cost-effective form of hydrogen to transport. Hydrogen may also be produced in smaller “distributed production” facilities, very near or at the point of end-use. Delivery methods for hydrogen fuel are determined by the production volume and delivery distance, as shown in Figure 8.

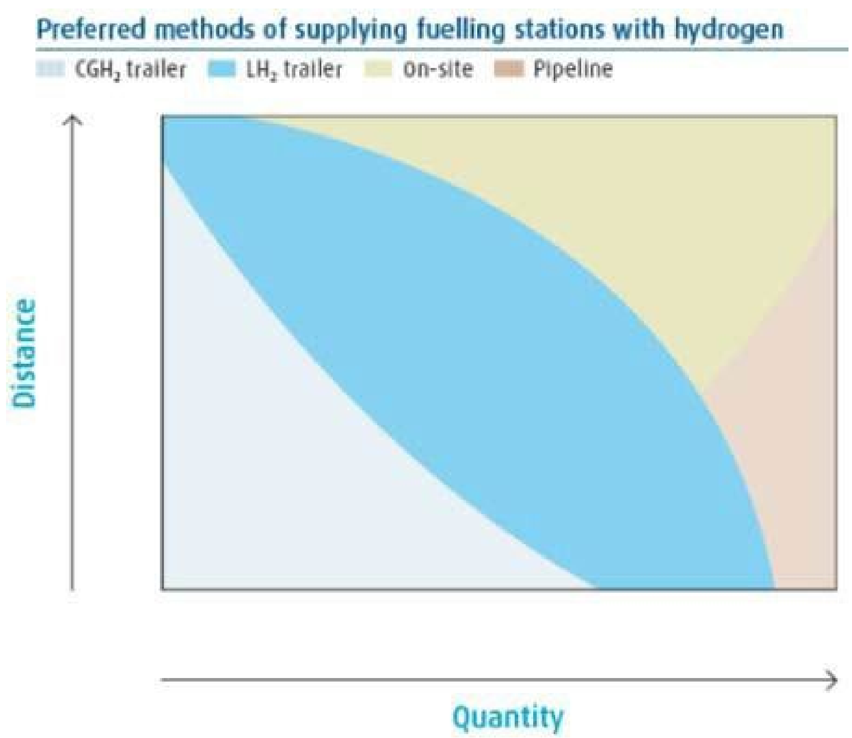


Figure 13: Preferred Hydrogen Supply Methods (image courtesy of The Linde Group)

There are various feasible hydrogen fuel production and delivery methods for transit agencies. The choice is most often based on fleet size and location.

Compressed Gaseous Hydrogen in Tube Trailers

Figure 14: Hydrogen Delivered Via Tube Trailer by Praxair

Compressed hydrogen tube trailers are typically used in low-volume commercial applications or temporary demonstration projects. Trucks transport vessels of compressed gaseous hydrogen for short distances to deliver hydrogen from a central facility. These tube trailers provide convenient and portable fueling solutions but are typically less efficient than permanent liquid hydrogen installations.

Limitations include the low storage capacity requiring frequent delivery and the low pressure of hydrogen delivered, which requires additional compression at the fueling station site. Nominal emissions are associated with the delivery to the site by internal combustion engine transport trucks.

Liquid hydrogen delivery and storage

Liquid hydrogen installations are an ideal solution for high-volume, permanent commercial installations, such as fueling stations for fuel cell transit bus fleets.

The energy density of liquid hydrogen is considerably higher than that of compressed hydrogen and is therefore generally a more cost-effective solution for large-scale use, as fewer journeys are necessary to transport the same quantity of energy.

Figure 15: Liquid Hydrogen Storage by Air Liquide

The liquid hydrogen is then vaporized to a high-pressure product for use at the bus depot. Again, some nominal emissions are associated with the delivery to the site by internal combustion engine transport trucks.

On-site steam methane reformation

Figure 16: Air Products PRISM On-Site Hydrogen Generation System

In North America today, more than 95% of hydrogen is produced by large-scale SMR.

This is the most cost-effective method of hydrogen production. Medium-scale reformers are available for producing on-site hydrogen from natural gas for hydrogen bus fleets.

Fully skidded, modular designs allow for low-cost installation at the bus depot in a compact footprint.

Also, renewable natural gas (RNG or biogas) can be a feedstock for the reformer to create renewable hydrogen in the SMR process. Although the SMR technology is popular and can be renewable, there are some emissions because of the process.

On-site electrolysis

Electrolysis is a promising option for hydrogen production from renewable resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. The resulting hydrogen is stored until it is needed to fuel the bus. Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used.

Figure 17: ITM Power's HFuel Unit Generates Hydrogen Gas From Water By Electrolysis

The table below summarizes the key characteristics of each hydrogen supply alternative.

Topic	Compressed Gaseous Hydrogen	Liquid Hydrogen	On-Site SMR	On-site electrolysis
Overall	Good for volumes <125kg/day	Excellent for large volumes	Good supplement for large volumes	Good supplement for large volumes
Distribution Costs	High; price drastically affected by location	Nominal; range flexibility	None	None
Price Volatility	Cost dependent on fuel prices but can be set with contract	Cost dependent on fuel prices but can be set with contract	Cost dependent on maintenance and fuel costs	Cost dependent on maintenance and electricity costs
Infrastructure Costs	Lower	Higher	Depends on production capacity	Depends on production capacity
Carbon Emission Reductions	Renewable hydrogen available at higher cost	Renewable hydrogen available at higher cost	Renewable biogas available at higher cost	Renewable energy is available at higher cost or renewable energy infrastructure can be installed on-site

Appendix III – Hydrogen Resources in North America

Ballard continues to collect the latest information on hydrogen production resources in the United States. You can find this information at the following link, please contact Ballard if you have updates, additions or questions

https://www.google.com/maps/d/u/1/edit?mid=1hYQD35CXe4tJAwjzQVMs8Ww_zuk-4OtW&usp=sharing